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DETECTION AND RECOGNITION

MODELS OF DOLPHIN SONAR SYSTEMS

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INTRODUCTION

Research has shown that dolphins possess highly sophisticated sonar capabilities. Several reviews and papers presented at the second international meeting on Animal Sonar Systems (Busnel and Fish, 1980) elucidated the sonar capabilities of dolphins. Nactigall (1980) discussed object size, shape and material composition discrimination by echolocating odontocetes. Murchison (1980) presented data on target detection and range resolution capabilities of Tursiops truncatus. Au (1980) discussed signals used by Tursiops in open waters. Data on target recognition of cylinders with varying wall thicknesses and material composition (Au and Hammer, 1980) and on sphere-cylinder discrimination (Au et al., 1980) were also presented. These and other studies indicate that dolphin sonars are superior to any man-made sonar systems for short ranges (two to three hundred meters), shallow water (typical of bays, inlets, and coastal waters). The dolphin sonar may be considered the premier sonar for the detection and recognition of slow moving or stationary targets in shallow waters where the reverberation and noise background levels are high.

The objective of this paper is to examine the dolphin sonar system from theoretical and empirical perspectives. Appropriate ideas and models which may improve our understanding of the echolocation process will also be considered. Human listening results using simulated dolphin echolocation signals to insonify targets will also be used to gain insights into available target cues on which target recognition and discrimination may be made by echolocating dolphins.

I. APPLICATION OF THE SONAR EQUATION

The noise-limited form of the sonar equation can be used to describe the target detection performance of a sonar. It equates the detection threshold (DT) to the echo-to-noise ratio when the target is just being detected, and can be expressed in dBs as (Urlick, 1983)

$$DT = \underbrace{SL - 2TL}_{\text{Echo level}} + \underbrace{TS - (NL - DI)}_{\text{Noise level}} \quad (1)$$

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where: SL = source level
 TL = transmission loss
 TS = target strength
 NL = background noise level
 DI = receiving directivity index

The equation is written in terms of intensity or the average acoustic power per unit area. However, when dealing with transient-like signals such as dolphin signals, echoes may be many times longer than the transmitted signal. An example of a simulated dolphin echolocation signal and an echo from a 7.62-cm diam. water-filled sphere are shown in Fig. 1. Therefore, eq. 1 should be transformed to a more generalized form involving energy flux density (Urick, 1983). This can be achieved by using the relation between intensity (I) and energy flux density (E) and the definition of TS,

$$I = \frac{1}{T} \int_0^T \frac{p^2(t) dt}{\rho c} = \frac{E}{T} \quad (2)$$

$$TS = 10 \text{ Log } \frac{\text{echo intensity 1 m from target}}{\text{incident intensity}} \quad (3)$$

Using eq. 2, the source level term of eq. 1 can now be written as

$$SL = 10 \text{ Log } I = SE - 10 \text{ Log } \tau_i \quad (4)$$

where the source energy flux density $SE = 10 \text{ Log } E$ and τ_i is the duration of the projected signal. Similarly, TS of eq. 4 can be rewritten as

$$TS = TS_E - 10 \text{ Log } (\tau_e / \tau_i) \quad (5)$$

where TS_E is the target strength based on the ratio of the energy in the echo over the incident energy, and τ_e is the duration of the echo. However, if we assume that dolphin detect signals in noise like an energy detector having a specific integration time of τ_{int} , then τ_{int} should be used in place of τ_e in eq. 5. Substituting eqs. 4 and 5 into eq. 1, we get the transient form of the sonar equation applicable to a dolphin

$$DT_E = DT - 10 \text{ Log } \tau_{int} = SE - 2TL + TS - (NL - DI) \quad (6)$$

The detection threshold, DT_E corresponds to the energy-to-noise ratio used in human psychophysics and is equal to $10 \text{ Log}(E_e/N_0)$, where E_e is the echo energy flux density and N_0 is the noise spectral density level. DT is the signal-to-noise ratio used in sonar engineering.

Peak-to-peak sound pressure level (SPL_{pp}) rather than energy flux density is normally measured. A simple relationship between E and SPL_{pp}

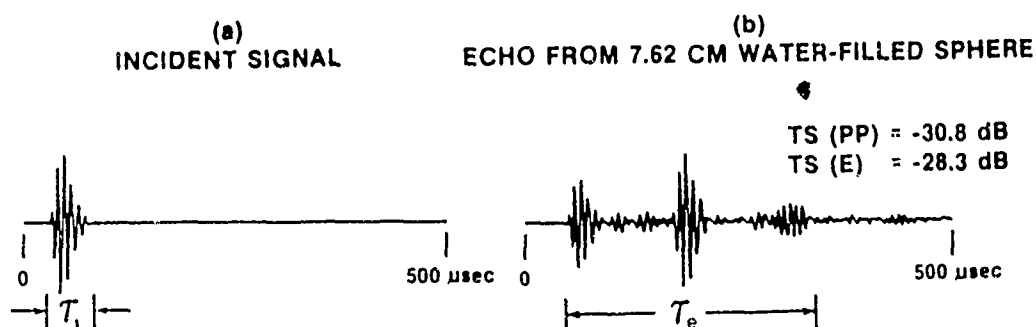


Fig. 1. Example of a simulated dolphin echolocation signal and the echo from a 7.62-cm diameter water-filled sphere.

can be derived by letting the acoustic signal equal $A \cdot s(t)$, where A is the peak amplitude and $s(t)$ is the waveform function ($|s(t)| \leq 1$). Then,

$$SPL_{pp}(dB) = 20 \text{ Log } (2A) = 20 \text{ Log } A + 6 \quad (7)$$

$$E_{pp}(dB) = SPL_{pp}(dB) + 10 \text{ Log } \left(\int_0^T s^2(t) dt \right) - 6. \quad (8)$$

The Log integral term does not vary much for dolphin signals in Kaneohe Bay, and is approximately -52 ± 1 dB. Equation 8 can now be expressed as

$$E(dB) = SPL_{pp}(dB) - 58 \quad (9)$$

Equation 8 along with the source level data of Au (1980) shown in Fig. 2 can be used to obtain estimates of SE in the sonar equation.

Values of the receiving directivity index, DI, were calculated by Au and Moore (1984) from measured receiving beam patterns of Tursiops. Their results are shown in Fig. 3 for frequencies of 30, 60 and 120 kHz. The linear curve fitted to the results can be expressed as

$$DI(dB) = 16.9 \text{ Log } f(\text{kHz}) - 14.5 \quad (10)$$

Au and Penner (1981) determined the detection threshold for two Tursiops using the maximum SE per trial. Large fluctuations in SE occurred in most click trains and it was not clear which clicks were used by the dolphins for target detection. Therefore, conservative estimates of

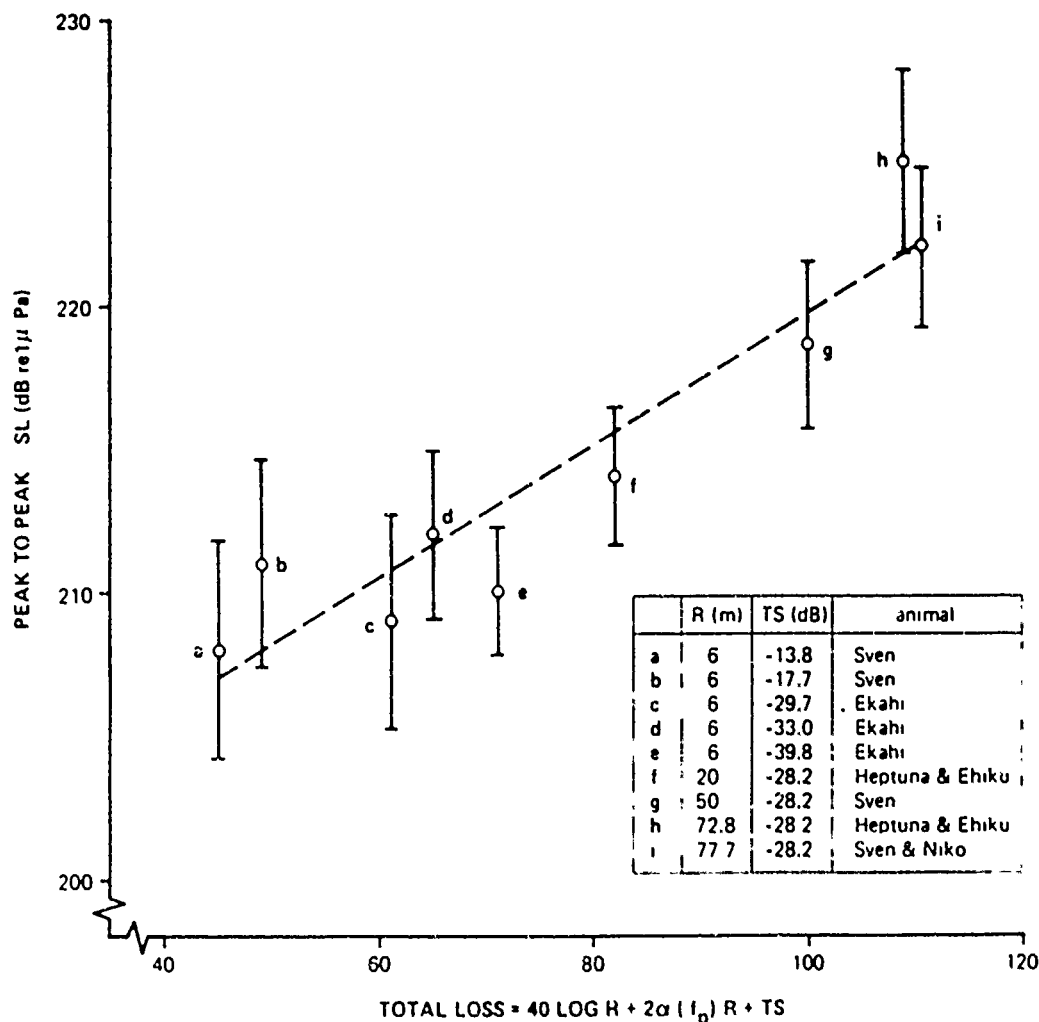


Fig. 2. Peak-to-peak source level of dolphin echolocation signals versus total loss for five animals performing different tasks.

DT_E representing the best S/N available to the dolphin were made using the largest SE. The average SE per trail was typically 4 to 5 dB below the maximum SE. Au (this volume) included the results of three other experiments with detection thresholds (DT_E) between 7.2 and 12.7 dB.

In comparing detection sensitivities between humans and dolphins we need to be aware that detectability of a signal is a function of the signal duration, frequency, and bandwidth, and the psychophysical testing procedure. Two-alternative forced-choice (2AFC) experiments with humans subjects indicate DT_E of 7.9 dB (Green et al., 1957) to 5 dB (Jeffress, 1968). McFadden (1968) using a Yes/No paradigm measured a DT_E of 10 dB for a 400 Hz, 125-msec signal in continuous and burst noise. Martin and Au (1986), using a Yes/No paradigm and simulated dolphin signals time stretched into the human auditory range obtained DT_E of 4.5 dB. Dolphin and human signal detection thresholds in noise seem to be similar despite differences in the methods and signals used.

II. DOLPHIN SONAR MODELED AS AN ENERGY DETECTOR

The threshold versus signal duration and the critical ratio experiments of Johnson (1968a,b) with Tursiops truncatus indicate that the animal's inner ear functions like the human inner ear and that the animal integrates acoustic energy in the same way as humans. Green and Swets (1966) have shown that an energy detector is a good analogue of the human auditory detection process. Therefore, it seems reasonable to approach the dolphin auditory detection process as an energy detector. Au and Moore (This volume) used an electronic "phantom target" to study signal

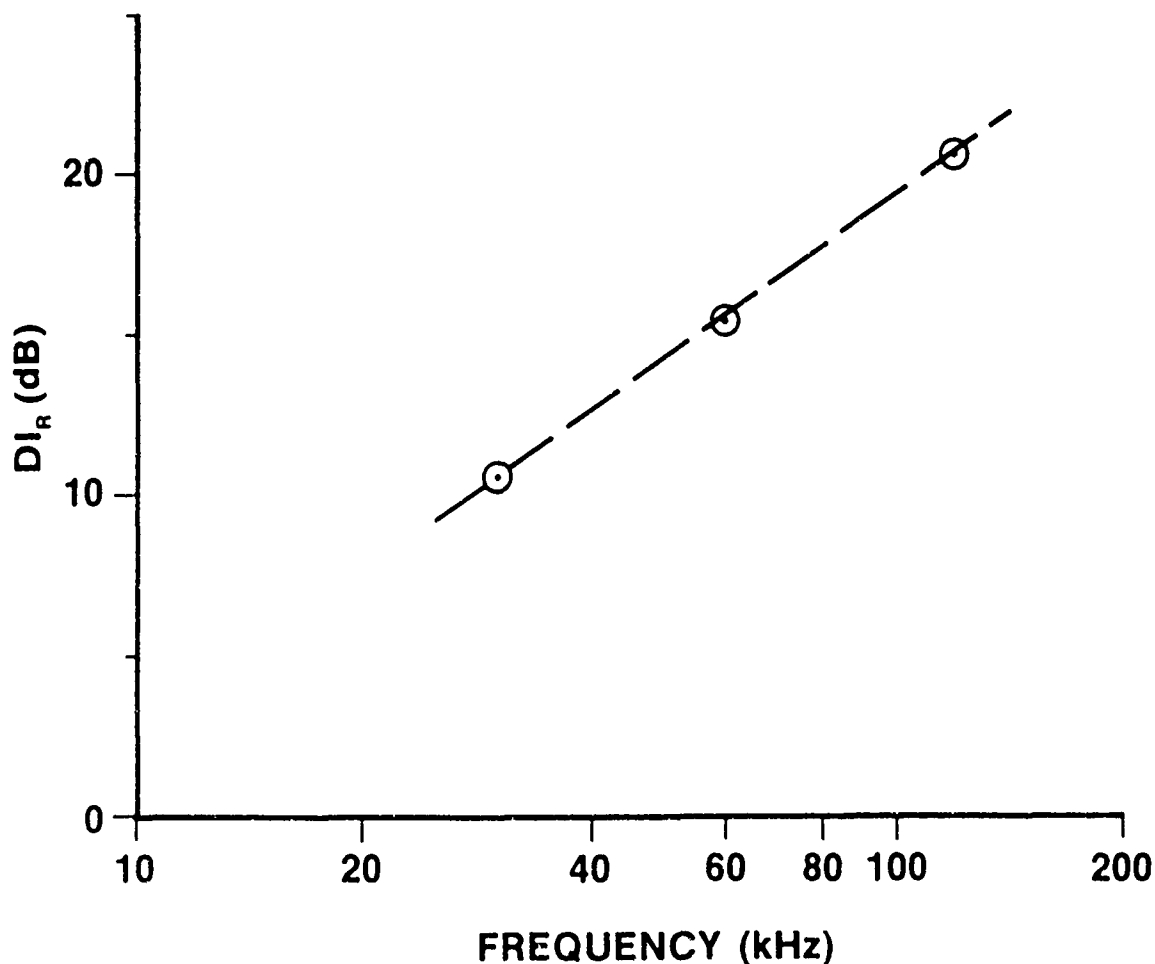


Fig. 3. Receiving directivity index for Tursiops truncatus as a function of frequency (From Au and Moore, 1984).

detection processes of a dolphin. One, two or three replicas of each click emitted were projected back to the animal. All pulses were within the integration time of the dolphin (Au and Moore, this volume). Their results are shown in Fig. 4, along with an energy detector response curve. The dolphin's performance followed the response of an energy detector.

Urkowitz (1967) examined the detection of a deterministic signal in white Gaussian noise using an energy detector and derived expressions for the correct detection and false alarm probabilities. The probability of a false alarm for a given threshold V_T is given by

$$P(FA) = 1 - \Pr(V_T \leq \chi^2_{2TW}) \quad (11)$$

where \Pr is the area under the chi-square distribution curve with $2TW$ (time-bandwidth) degrees of freedom. For the same threshold level V_T , the probability of a correct detection is given by

$$P(D) = 1 - \Pr(V_T/G \leq \chi^2_D) \quad (12)$$

where: $D = (2TW + E/N_0)^2 / (2TW + 2E/N_0) \quad (13)$

$$G = (2TW + 2E/N_0) / (2TW + E/N_0). \quad (14)$$

\Pr is now the area under the noncentral chi-square distribution with a modified number of degrees of freedom D and a threshold divisor G .

These expressions derived by Urkowitz (1967) were applied to dolphin detection in noise data by assuming an unbiased detector in determining the probability of a correct response $P(C)$ from $P(FA)$ and $P(D)$. The calculation was done by first choosing desired values of $P(FA)$ and $2TW$ and then determining V_T by an iterative procedure. Then with the iterated value of V_T ,

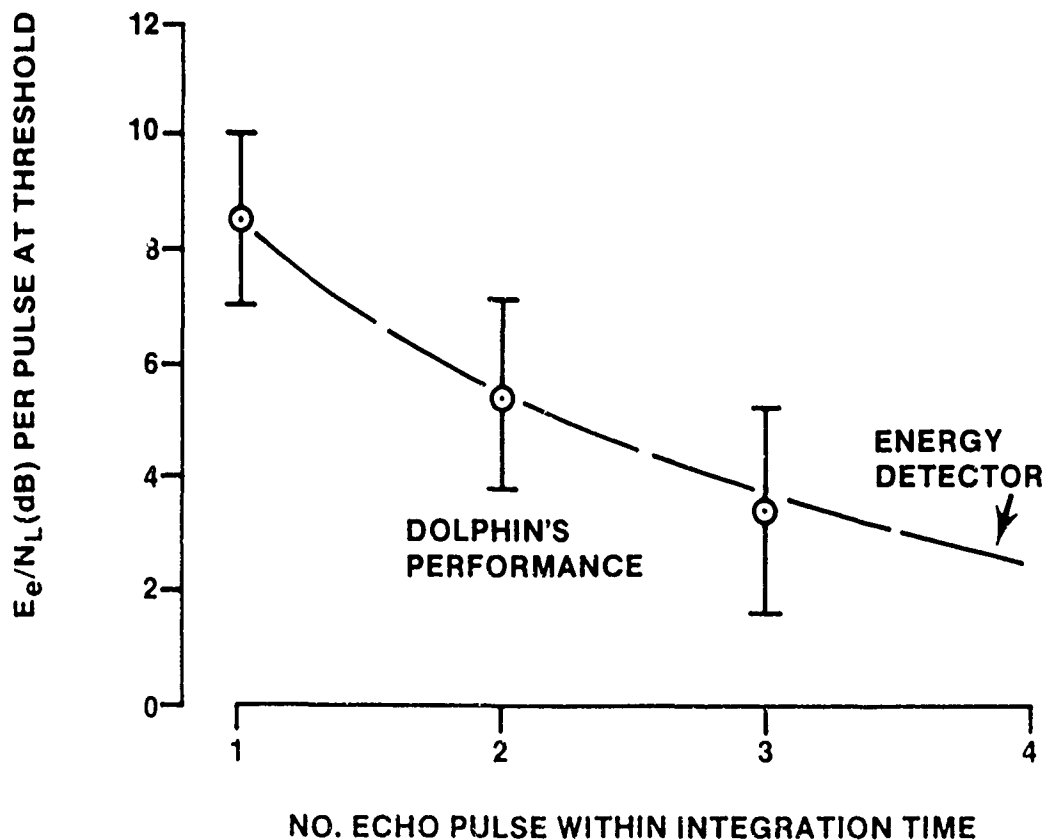


Fig.4. Dolphin detection threshold in noise versus number of pulses within an integration time (From Au and Moore, this volume).

$P(D)$ was calculated for different values of E/N_0 . The procedure was continued for different 2TW degrees of freedom, until the values of $P(C)$ were obtained as a function of E/N_0 which best fitted the dolphin data. The performance data for Tursiops detecting targets in masking noise in three different studies are shown in Fig. 5 along with the results of Urkowitz energy detection model for 2TW = 22.

Urkowitz energy detection model agrees well with the dolphins' performance results, further supporting the notion of the dolphin being an energy detector. The unbiased detector assumption used to derive $P(C)$ is a good one for signal-to-noise conditions at or above the 75% correct threshold. Tursiops tends to be unbiased for high signal-to-noise conditions (Au and Synder, 1980; Au and Penner, 1981; Au and Moore, this volume).

McGill (1968) considered the detection of a signal known except for phase using an energy detector in a 2AFC procedure. Au and Penner (1981) applied McGill's expression to a Yes/No paradigm by determining $d'(2AFC)$ from the tables of Elliot (1964), and by using the relation $d'(2AFC) = 2 d'(Y/N)$ (Tanner and Sorkin, 1972). The values of $P(C)$ was then calculated as a function of $d'(Y/N)$ assuming an unbiased detector. McGill's formula also fitted the dolphins' performance.

III TARGET RECOGNITION AND DISCRIMINATION

Hammer and Au (1980) examined targets used in a recognition experiment with simulated dolphin signals. Echoes were passed through a matched filter having the transmitter signal as the reference. The envelopes of the matched filter provided information to explain the dolphin's performance. Times of arrival and shapes of the matched filter envelope for the different echo highlights, especially the second component, were found to be important. They suggested that dolphins may use time-separation pitch (TSP) cues caused by the interaction of highly correlated highlights.

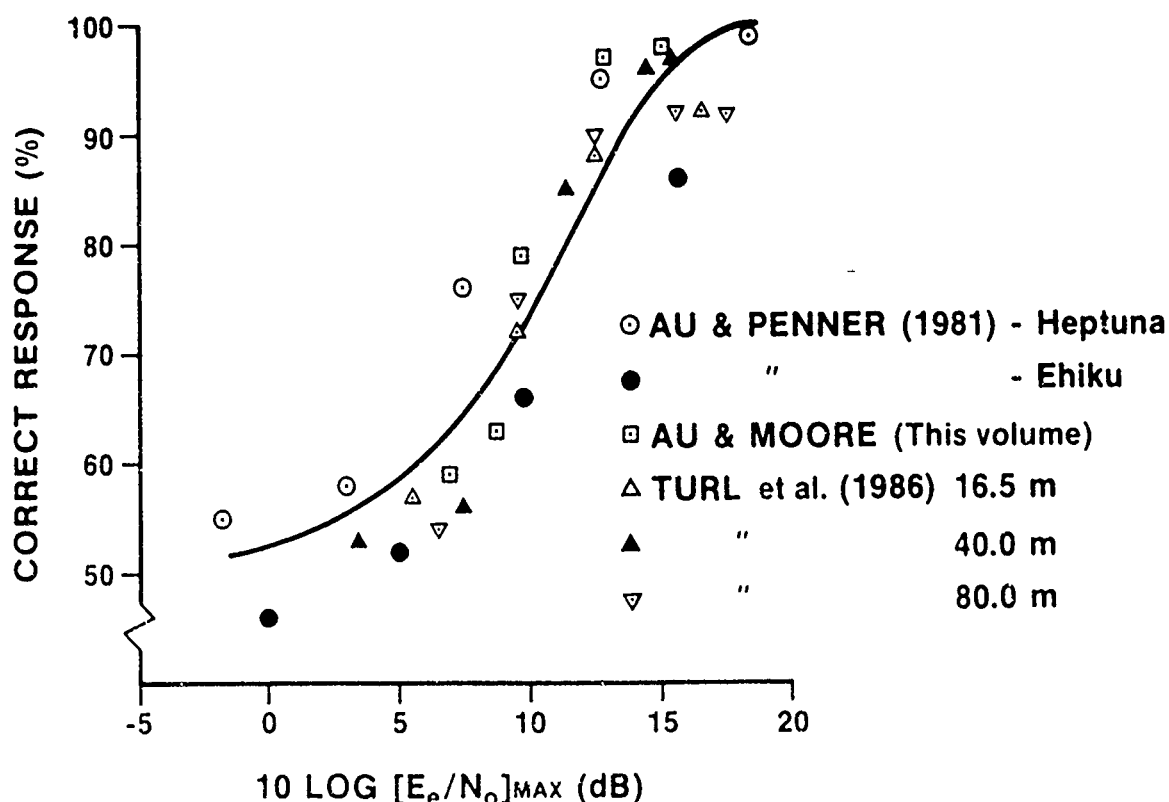


Fig. 5. Dolphin performance results and Urkowitz energy detector model.

Altes (1980) proposed a viable dolphin echolocation model which involved the time-frequency energy density or spectrogram of echoes. The time-frequency energy density function contains information on both high-light distribution and energy spectrum. Target detection, recognition, and discrimination would be achieved by correlating the spectrogram of echoes with previously measured spectrograms of known targets. Altes spectrogram model seems consistent with the TSP model of Hammer and Au (1980), and with the use of energy detection.

Martin and Au (1982, 1986) took a different approach in studying target discrimination by dolphins. They performed experiments using the excellent discrimination and pattern recognition capabilities of the human auditory system to analyze target echoes from the same targets used in dolphin experiments. Fish et al. (1976) previously demonstrated that instrumented human divers, listening to echoes produced by projecting dolphin-like signals, could discriminate the thickness and material composition of metallic plates as well as or better than dolphins. The echoes were time-stretched into the human auditory range. Martin and Au (1982, 1986) used a similar technique but performed human listening experiments in a sound booth. Their specific objective was to determine what acoustic cues were available for discrimination.

Targets were examined acoustically using a monostatic sonar system (see Au and Synder, 1980) that projected a broadband simulated dolphin signal. The echoes were digitized at a sample rate of 1 MHz and stored on magnetic tape. The digitized echoes were played back to humans at a sample rate of 20 KHz, which effectively stretched the echoes by a factor of 50 and lowered the frequency by a factor of 50. For each trial, one of ten echoes was presented to the subjects at a rate of 4 echoes per second. The specific echo in a set of ten echoes per target was randomly selected for each trial.

A. Discrimination of cylindrical targets

Human subjects could easily discriminate standard aluminum cylinders from probe targets used in the general discrimination and material composition experiment of Hammer and Au (1980). For the general discrimination task, the two standard aluminum cylinders had outer diameters of 3.81 cm and 7.62 cm with wall thicknesses of 0.64 and 0.95 cm, respectively. The probe targets are described in Table 1. The discrimination task was found to be trivial even though some of the probes were aluminum cylinders, solid and hollow.

In the material composition discrimination task, subjects had to discriminate two aluminum standards from targets made of steel, bronze and glass. The targets had one of two wall thicknesses, 0.32 and 0.40 cm and outer diameters, 3.81 and 7.62 cm, respectively. The dolphin could discriminate the aluminum standards from the bronze and steel probes but classified the glass probes with the aluminum standards. The average

Table 1. Probe targets used in the general discrimination experiment.

Reference	IP1	IP2	IP3	IP4	IP5	IP6	IP7	IP8
Composition	Al	CPN	Al	CPN	Al	CRK	Al	PVC
Wall (cm)	0.48	solid	solid	solid	0.64	solid	solid	0.79
O.D. (cm)	6.35	6.35	3.81	4.06	11.43	11.43	7.62	7.62

performance of three human subjects in the aluminum versus steel and aluminum versus bronze was 98% and 95% correct, respectively. Subjects first determined whether an echo originated from a large or small cylinder based on duration and TSP cues. Echoes from the large cylinders had lower TSP and longer durations. Subjects reported that the small aluminum had lower TSP than the small bronze cylinder and the large aluminum had a TSP cue whereas the large bronze did not. Examples of the target echoes are shown in Fig. 6 for the small cylinders. One can see that the aluminum should have a higher TSP than the small bronze target. The aluminum versus steel discrimination was based on hearing clearly perceptible TSP with the aluminum targets and less perceptible TSP with the steel targets.

Schusterman, et al. (1980) trained the dolphin used by Hammer and Au (1980) to discriminate between the small aluminum and glass targets using a two-alternative forced-choice paradigm. They were not able to train the animal to discriminate between the large aluminum and glass cylinders. In the human listening experiment, four subjects discriminated between the aluminum and glass targets with performance accuracy varying from 74% to 94% correct. The main discrimination cue was difference in echo durations between the aluminum and glass echoes. Typical examples of the echoes from the targets are shown in Fig. 7. The glass echoes damped out approximately 14 and 5 ms before the aluminum echoes for the small and large targets, respectively. The duration difference may not have been perceptible to the dolphin, but could be perceived by humans as a result of the time expansion of 50. The ambient noise was not a problem for the dolphin since it typically operated with E/N_0 in excess of 40 to 50 dB.

The duration cues for the large aluminum versus glass discrimination were examined further by truncating the echoes between groups of highlights, indicated by the tick marks in Fig. 7. The truncation caused the signals to be of equal duration, eliminating any duration cues. The performance of two subjects as a function of the signal length is shown in Fig. 8. Discrimination accuracy decreased as the signals became shorter. The final truncation eliminated all but the first two echo components, yet the subjects were able to discriminate the signals above 70% correct. The

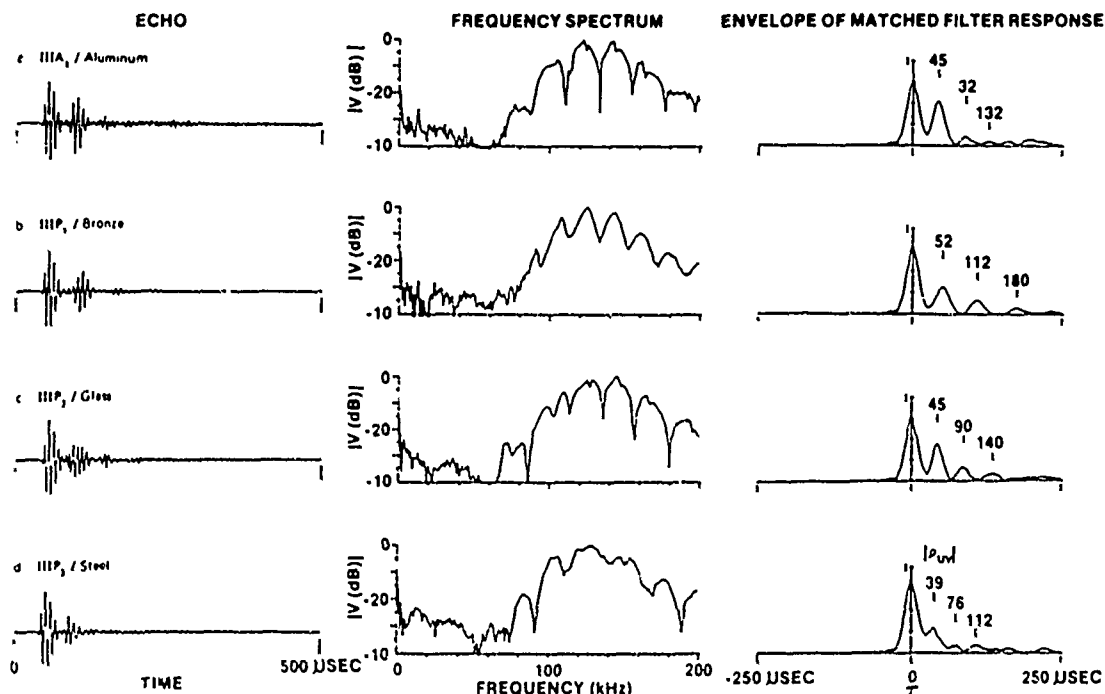


Fig. 6. Backscatter measurements of the 3.81-cm cylinders. Highlight arrival times are indicated on the matched filter results. (From Hammer and Au, 1980).

ECHO WAVEFORM

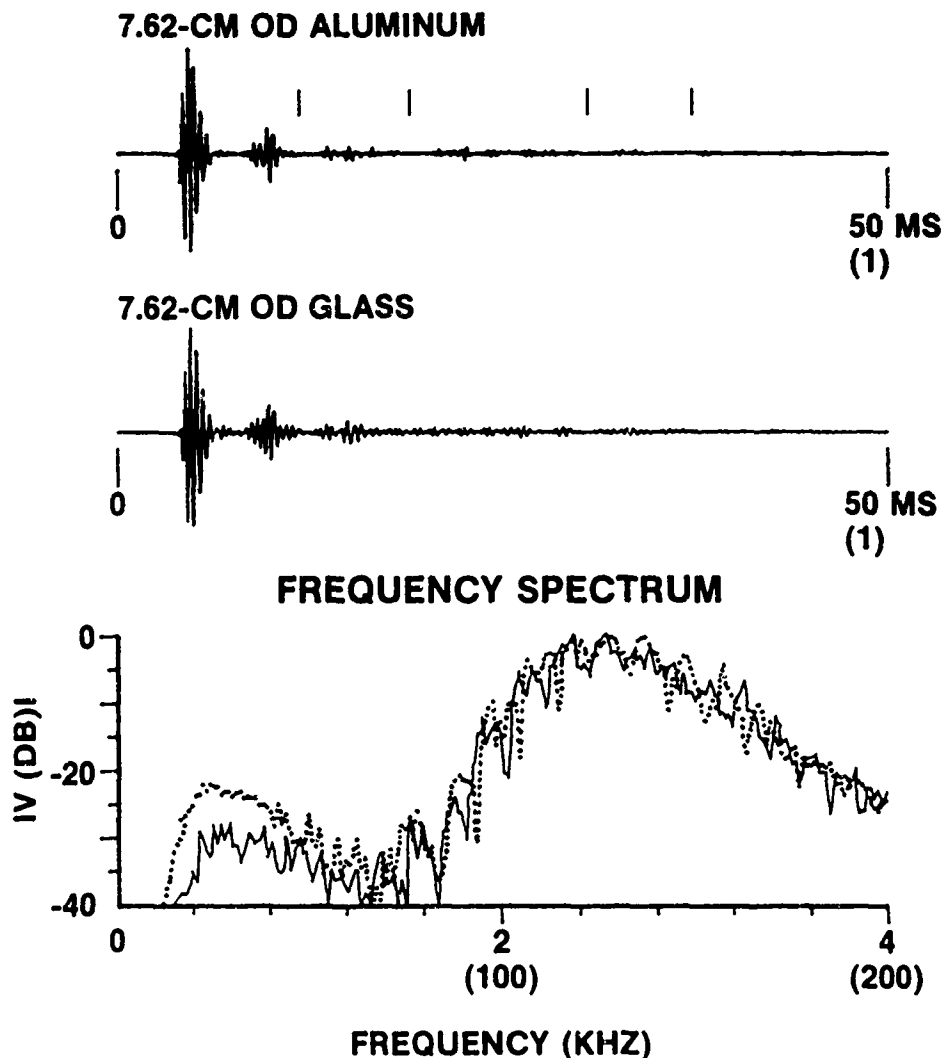


Fig. 7. Echoes from 7.62-cm aluminum (solid) and glass (dashed) cylinders (From Martin and Au, 1986).

time between the first and second echo components was virtually the same for both targets. Thus, the discrimination was based on cues other than TSP differences. The subjects indicated that the glass target had a slightly higher "click pitch" than the aluminum. This cue was difficult to extract and was not always reliable.

B. Discrimination of Cylindrical Target in Noise

Martin and Au (1986) next performed material composition discrimination in noise. The results are shown in Fig. 9 for the aluminum versus glass discrimination. For the 3.81-cm cylinders, E/N_0 had to be at least 10 dB greater than the detection threshold in noise before a subject could discriminate above 75% correct. For the 7.62-cm cylinders, E/N_0 had to be at least 30 dB greater than the detection threshold. Subject NN gained a sudden insight into discriminating the 7.62-cm cylinders at the 25 and 30 dB signal-to-noise ratio. In general, learning the discrimination was insightful, as subjects began to utilize different cues.

C. Sphere - Cylinder Discrimination

Human discrimination between spheres and cylinders was measured using foam, solid aluminum and water-filled steel targets. Au et al. (1980)

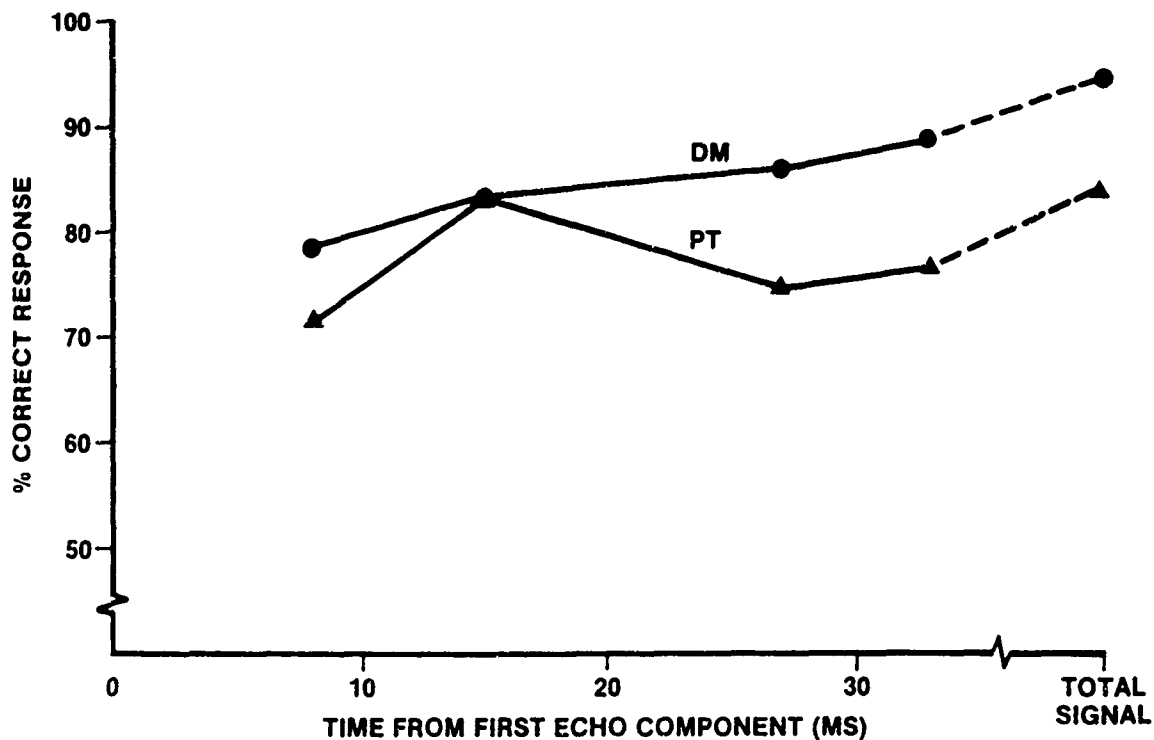


Fig. 8. Human discrimination of 7.62-cm aluminum and glass cylinders versus signal duration (From Martin and Au, 1982).

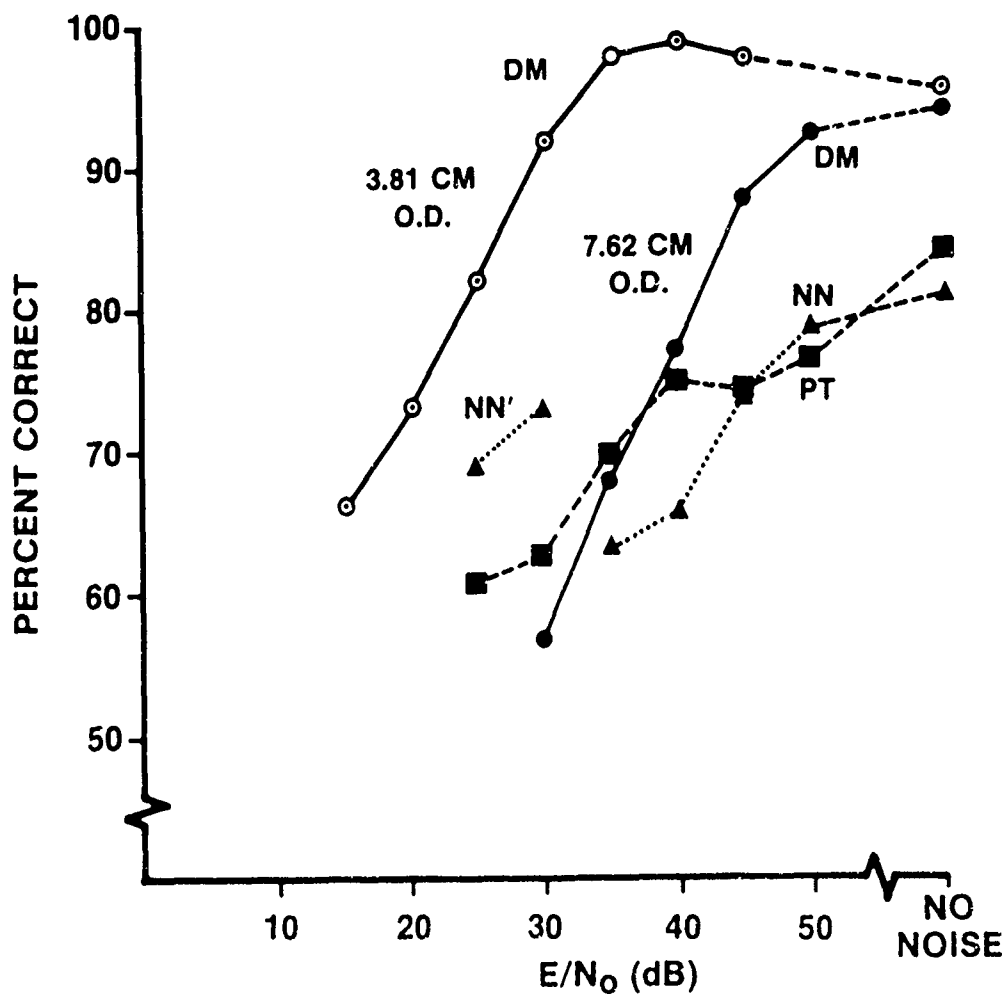


Fig. 9. Aluminum versus glass discrimination results as a function of the signal energy-to-noise ratio (From Martin and Au, 1986).

demonstrated that an echolocating dolphin could discriminate between foam spheres and cylinders. They speculated that echoes returning via a surface reflected path were larger in amplitude for spheres than for cylinders. However, when the surface reflected echo component was blocked with an absorbent "horsehair" mat, the dolphin still performed the discrimination. The same foam targets were also used with humans. Discrimination results pooled across subjects are given in Table 2. The average probability of correct discrimination varied between 84% and 96%. The windowed results indicated that surface echo components did provide cues but both the dolphin and humans could perform the discrimination task without these cues.

Subjects reported that two cues used for discrimination were a higher pitch associated with cylinder echoes and the presence of low-frequency reverberation in the sphere echoes. The target strength of a cylinder increases with frequency and is constant with frequency for a sphere (Urick, 1983). An example of echoes from a foam sphere and cylinder is shown in Fig. 10. The sphere echo has a low amplitude portion following the main reflection; the cylinder echo does not. The spectra for the cylinder has more energy than the sphere's at higher frequencies.

Performance of two subjects in the solid aluminum sphere-cylinder and the water-filled steel sphere-cylinder was between 94% and 100% correct. Subjects reported that the metal target echoes did not sound like foam echoes. However, the same discrimination cues were used: a higher click pitch for cylinders, and more reverberation for spheres.

D. Target Detection in Reverberation

The clutter screen experiment of Au and Turl (1983) was examined with the targets in the plane of the clutter screen. The human and dolphin performance as a function of the peak-to-peak echo-to-reverberation ratio are shown in Fig. 11. The cue used by the humans was the presence of a "click" sound from the targets. The echoes from the clutter screen sounded diffused, whereas the echoes from the aluminum cylinders sounded like compact clicks with a definite TSP. Subjects learned to integrate only over the duration of the target echo.

Table 2. Foam sphere versus cylinder dolphin discrimination results. The windowed results refer to echoes which had the air-water surface reflected components truncated.

Spheres (Dia.)	Cylinders (Dia. x Length)	Presentation Schedule	Total Signal	Windowed Signal
S1: 10.2 cm	C1: 1.9 x 4.9 cm	S2 vs C4	96%	88%
S2: 12.7 cm	C2: 2.5 x 3.8 cm	S2/S3 vs C3/C4	93%	85%
S3: 15.2 cm	C3: 2.5 x 5.1 cm	S2/S3 vs C1/C4	88%	81%
	C4: 3.8 x 5.4 cm	S1/S2 vs C4/C5	84%	--
	C5: 3.8 x 5.1 cm	S1/S2 vs C2/C4	91%	83%

ECHO WAVEFORM

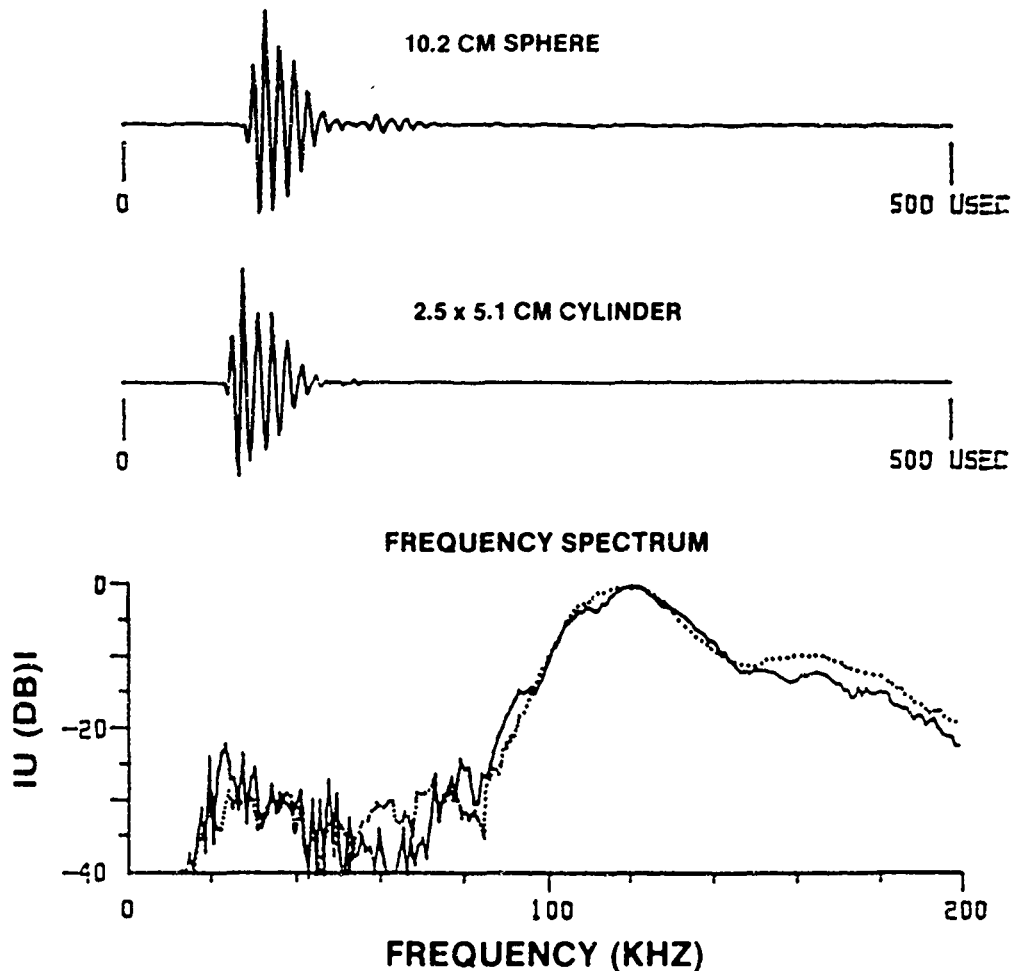


Fig. 10. Echoes from foam sphere (solid) and cylinder (dotted). (From Martin and Au, 1986).

E. Aspect Independent Discrimination of Cylinders

The final experiment involved a material composition discrimination of cylinders at various aspects. The procedure involved training the dolphin to discriminate between two targets at the baseline aspects of 0, 45, and 90°, where 0° was the broadside aspect. After the dolphin could perform the discrimination at 90% correct for the baseline aspects, probe trials at different aspects was used. In the first discrimination task, aluminum versus steel, the dolphin performance did not reach the 90% criterion for 45 and 90° aspect. An easier discrimination of aluminum versus coral rock was then chosen. The dolphin's results are shown in Table 3, which includes both the baseline (shaded) and probe results.

A similar procedure was used with the humans but with a wider variety of targets. Subjects were trained to discriminate between pairs of targets for the baseline angles. After achieving near 100% correct performance on the baseline angles, sessions were made more complex by presenting echoes from seven aspects, 0, 15, 30, 45, 60, 75 and 90°. The human results pooled over the four subjects are shown in Table 4. As with the dolphin, the humans could perform the aluminum versus rock discrimination readily but had problems with the aluminum versus steel discrimination (4th column of Table 4). When the subjects were given the possibility of having any one of seven aspects presented for a given trial, performance at the baseline angles deteriorated. No specific cues could be focused on in this experiment since the echoes were so complex. However, the human

Table 3. Dolphin discrimination results as a function of aspect angle of the targets (From Martin and Au, 1986).

BASELINE PERFORMANCE

0°		45°		90°	
AL	ROCK	AL	ROCK	AL	ROCK
100%	94%	91%	89%	100%	96%

PROBE SESSIONS

0°		15°		30°		45°		60°		75°		90°	
AL	ROCK	AL	ROCK	AL	ROCK	AL	ROCK	AL	ROCK	AL	ROCK	AL	ROCK
100%	100%	98%	97%	96%	100%	100%	100%	100%	100%	100%	100%	100%	96%

subjects indicated that echoes at the 45° aspect angle contained the most information pertinent to the other angles.

IV. DISCUSSION AND CONCLUSIONS

An echolocating dolphin's ability to detect target echoes in noise and to make fine discrimination of target features seems similar to human auditory detection and pattern recognition capabilities. Although human

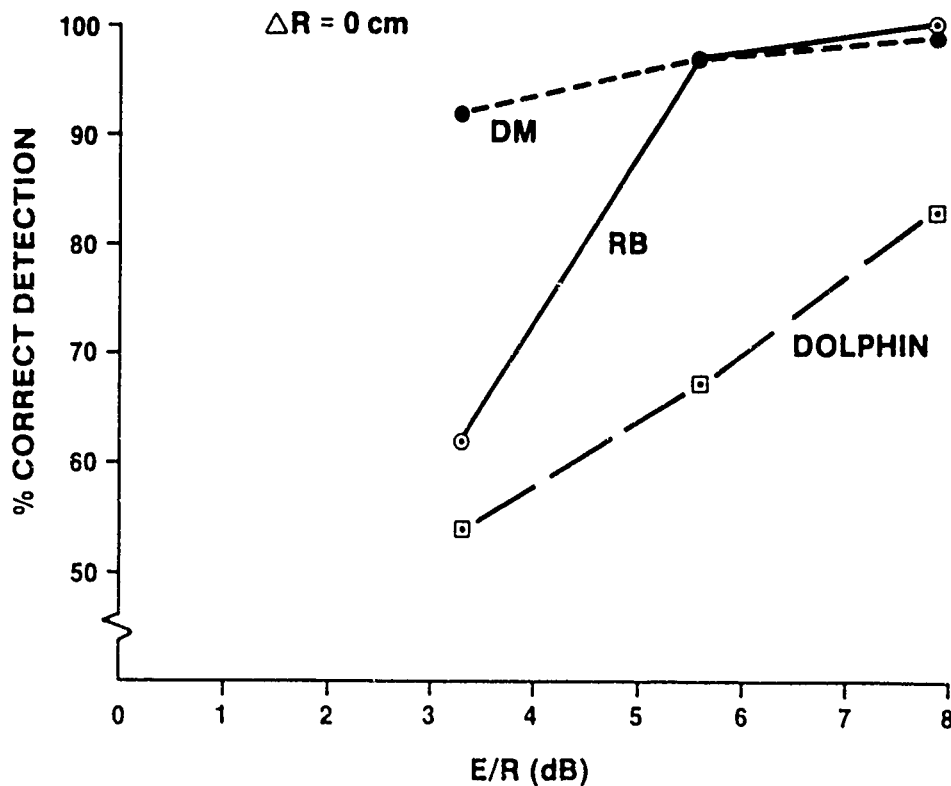


Fig. 11. Target detection in clutter performance results for humans and dolphin (From Martin and Au, 1986).

Table 4. Human discrimination results as a function of target aspect angle for different target pairs. The values in each column are the percent correct results in identifying a particular target in a target pair (From Martin and Au, 1986).

	HOLLOW ALUM	CORAL ROCK	HOLLOW ALUM	SOLID ALUM	SOLID ALUM	CORAL ROCK	HOLLOW ALUM	HOLLOW STEEL	ALUM WATER	ALUM AIR
0°	89	92	56	93	93	94	93	97	90	100
15°	98	93	99	76	88	91	97	57	100	80
30°	89	93	77	73	94	92	53	91	69	91
45°	88	98	83	93	81	93	84	87	95	91
60°	81	85	81	90	80	87	53	69	71	92
75°	98	80	91	58	95	70	68	71	83	98
90°	97	96	97	98	97	92	100	95	99	98

hearing experiments were performed differently and with different stimuli, detection thresholds of dolphin and man are comparable. The question that comes immediately to mind is "why does the dolphin sonar perform better than man-made sonars in shallow water environments?" There are several factors inherent in dolphins that may provide advantages over man-made sonars. A dolphin is a highly mobile aquatic mammal that is capable of using its sonar while in motion, going to different depths and locations, and looking at objects from various aspects. Reverberation and noise observed from one aspect may be different when observed at other aspects, and locations. The dolphin may also have good long term auditory and spatial memory which would be effective in recognizing desired targets in specific positions and in spatial pattern recognition of echoes from various locations.

Most man-made active sonars have been designed to eliminate the human auditory capabilities from the system. Therefore, the excellent analysis and pattern recognition capabilities of the human auditory system are ignored. When a listening capability is included in an active sonar, less than ideal kinds of signals are often used: narrowband pulse tones or continuous transmission frequency modulated signals (CTFM). Neither of these signals possess the time resolution capabilities of broadband transient-like pulses that dolphins use.

Human listening experiments using dolphin-like sonar signals can be useful in understanding target cues and processing methods needed to extract them. The human listening experiments of Martin and Au (1982, 1986) indicated that differences in time-separation pitch associated with correlated echo highlights and differences in echo duration were the predominant discrimination cues in almost all of the tasks. Duration cues as much as 30 dB below the peak level of the primary echo component were found to be important and useful. Only in the sphere-cylinder and truncated aluminum-glass discriminations was spectral information in the form of click pitch an important cue. These cues used by the human listeners may be the same cues used by echolocating dolphins. It seems that time domain processing of highlight separation and highlight amplitudes within echoes may provide most of the target information to the dolphin. Therefore, broadband transient-like echolocation signals with good time resolution would be most useful to dolphins and humans.

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